A NEW FAULT RECOVERY MECHANISM FOR SUPERCONDUCTING CAVITY FAILURE IN C-ADS*

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Abstract

For proton linear accelerators used in applications such as C-ADS, due to the nature of the operation, it is essential to have beam failures at the rate several orders of magnitude lower than usual performance of similar accelerators. A fault-tolerant mechanism should be mandatorily imposed in order to maintain short recovery time, high uptime and extremely low frequency of beam loss. This paper proposes an innovative and challenging way for compensation and rematch of cavity failure using fast electronic devices and Field Programmable Gate Array (FPGA) instead of embedded computers to complete the computation of beam dynamics. Due to the high arithmetic-computing-speed, good portability and repeatability, it is possible to realize calculation and re-adjustment online. In order to achieve the goal of instantaneous compensation and rematch, an advanced hardware design methodology including high-level synthesis and an improved genetic algorithm will be used.

INTRODUCTION

The threat of exhaustion of global energy resources has been perplexing human society. Under this background, the Accelerator Driven Sub-critical System (ADS) not only has the advantage of producing clean and efficient nuclear energy, but also deals with lots of problems with nuclear waste. ADS, as a kind of current high power accelerator, unexpected beam trips will be considered as accelerator failure, even leading to the serious change of temperature and thermal stress in the reactor core, which may eventually results in the permanent damage of facilities. Therefore, the extremely high reliability and availability for C-ADS will be proposed [1, 2], as shown in Table 1.To reach such an ambitious goal, there are following measures [3]: (1) a high degree of redundancy, especially for linac injector and RF power system. (2) high reliability of every linac components which has to be overdesigned. (3) fault-tolerance capabilities have to be considered. When any cavity or solenoid failure, there are the neighbouring elements or every components in the superconducting RF linac operating in the process of compensation and rematch. In this paper, the concept of compensation about fault-tolerance will be presented in beam dynamics simulation, as well as the hardware implementation of the mechanism. Except this, a hardware model with space charge and a kind of hardware algorithm including high-level synthesis will be used.

Table 1: Main Parameters of C-ADS Linac

Parameters	Design	
Particle	proton	
Energy	1.5	GeV
Current	10	mA
Beam Power	15	MW
RF Frequency	(162.5)/325/650	MHz
Duty Factor	100	%
Beam Loss	<1	%
Beam Trips/Year	<2500	1s<t≤10
	<2500	10s<t≤5min
	<25	t>5min

THE MODEL WITH SPACE CHARGE IN NEW METHOD

The compensation of superconducting cavity or solenoid can be divided into general compensation and local compensation [3]. “General compensation” means that all the cavities downstream of fault cavity attend the compensation, while “local compensation” is related to the neighbouring elements. The general compensation has the low demand of the performance of each cavity, but it needs all cavities act at the same time, which means RF control should be extremely accurate. By contrast, the local compensation is easier and only needs few elements. However, it is hard on the elements which attend the compensation.

The most representative work is on the SNS. Their compensation can be classified to the general compensation and the whole process will cost about few minutes, which can’t be satisfied the requirement of ADS. When their cavities failed, the machine will look up the database to find the data of compensation which was already calculated. This way to accomplish compensation cost so much time both before the compensation and during the compensation. Except for this method, this paper gives another way to achieve the compensation by the hardware implementation of the scheme using fast electronic devices and Field Programmable Gate Array (FPGA). Here we give the preliminary diagram of the injector of C-ADS, as shown in Fig.1. This kind of method has its own advantages [4].

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* Work support by Natural Science Foundation of China (11575216)

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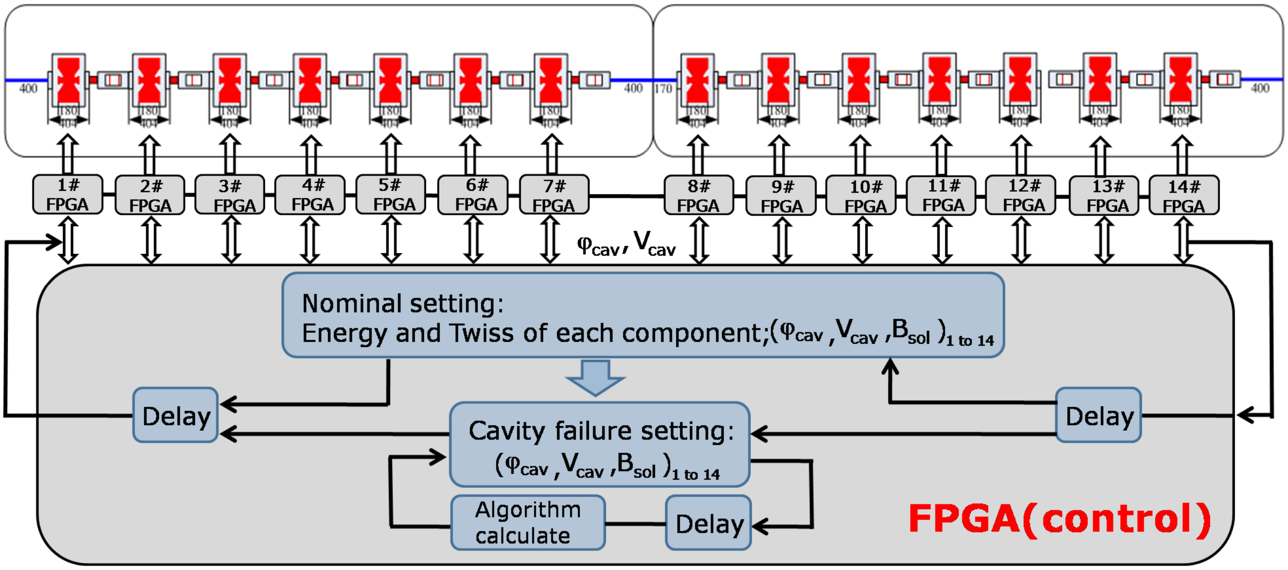

Figure 1: Diagram of the hardware compensation in C-ADS

(1) Arithmetic computing speed is higher. Parallel calculating and synchronous processing are the characteristics of FPGAs, which means it will save a lot of time during the process of calculation and finding the optimal solutions.

(2) Instantaneous compensation and rematch is easier. Not only is the computing speed higher for FPGAs, but it is also an easier way to connect with the low level RF system, EPICS, and other types of hardware facilities on the accelerator to make instantaneous compensation and rematch possible.

(3) Good portability and repeatability. Calculating by FPGAs can operate independently of some specific components. Because of modular design, it is much easier to get new results with the FPGA than the look-up-table way. The new method has advantages for subsequent modification and upgrade.

FPGA is consisted of lots of logic gate. The easiest way to get the result of algorithm is to use addition, subtraction, multiplication. Because of this, we choose linear basis function models [5], as shown in Eq. 1.

$$\mathrm{y(x, w)} = w_0 + \sum_{j=1}^{M-1} w_j \phi_j(x)\,. \tag{1}$$

$\phi_j(x)$ are known as basis functions, which can be fixed as nonlinear functions. We take the gain as an example. Gain is related to the kinetic energy, synchronous phase and Eacc. Here we choose second-order term to take the place of $\phi_j(x)$. Except for the gain, the model of transfer matrix without space charge is also built. In the model, we first choose the structure of “drift + gap + drift” to be equivalent to cavity. The way of building model not only can simplify the algorithm operating in the FPGA, but also can make the work of compensation on the real facility, which can test and prove the whole system of compensation.

Considering the space charge, the main components should be divided into short slices and insert the matrices of space charge [6], which means the polynomial model is a suitable format for this scenario. The space charge effect treated as a thin lens is shown in Eq.2.

$$R_{ce} = \left[\begin{array}{cc|cc|cc} 1 & 0 & 0 & 0 & 0 & 0 \\ K_x & 1 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & K_y & 1 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & K_z & 1 \end{array}\right]. \tag{2}$$

where $K_x = \frac{qc\Delta s}{(m_0c^2)^2\beta^2\gamma}E_x$, $K_y = \frac{qc\Delta s}{(m_0c^2)^2\beta^2\gamma}E_y$, $K_z = \frac{qc\Delta s}{(m_0c^2)^2\beta^2\gamma^3}E_z$ are the electrical field components in three directions. At the same time, each item can be equivalent by polynomial.

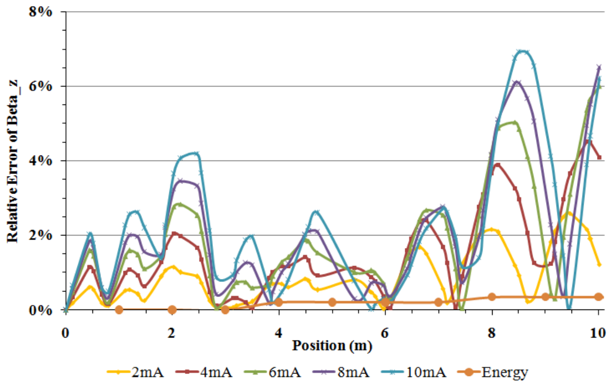

Figure 2: Relative error of energy and longitudinal beta at different beam current.

The relative error of different currents and energy between TRACEWIN and hardware model are shown in Fig.2. Figure 2 only shows the longitudinal beta about the 10MeV injector in C-ADS. With the increase of current, the space-charge effect brings about more error, but this kind of error can be controlled in several periods, which means the error will not influence local compensation.

THE GENETIC ALGORITHM IN NEW METHOD

Cavity failures bring about not only loss of energy but also mismatching which eventually leads to beam loss. How to re-adjust to complete the compensation and rematch can be treated as a problem of finding optimal solution, which can be solved by combining the equivalent model with some algorithms. Genetic algorithm [7] is a good choice to get near-optimal solutions by iteration. A flowchart for a genetic algorithm applied to an FPGA is shown in Fig. 3.

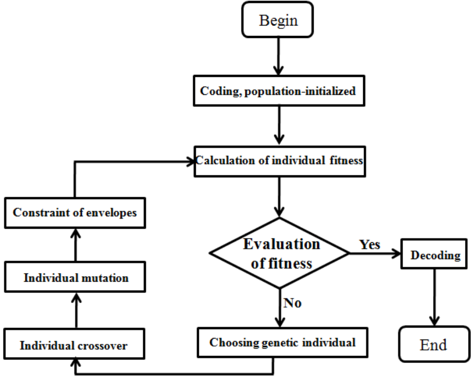

Figure 3: Flowchart for the genetic algorithm applied in the compensation and rematch.

It is different from traditional genetic algorithm in two aspects: Firstly, the constraint of envelops is added during the calculation of objective function. Secondly, the factors which decide the result of compensation and rematch have their own weights. Taking the 10 MeV injector I of C-ADS as an example, the energy and TWISS parameters at the match point are shown in Table 2.

Table 2: Comparison of Nominal Parameter at Match Point and after Compensation and Rematch

Parameters	Nominal	After	Mismatch Factor
Beta-x	2.8104	2.9085	0.514%
Alpha-x	-0.7873	-0.8117	
Beta-y	2.8739	2.9311	2.24%
Alpha-y	-0.8104	-0.7973	
Beta-z	1.3586	1.4331	2.56%
Alpha-z	0.3725	0.3909	
Energy	9.3809	9.3656	--

The model about the lattice of Injector I has been tested based on Xilinx Kintex7 series FPGA platform. All the ports and timing sequence has been tested. The mismatch factors in three directions are smaller than 3%, which is satisfied with the requirement of design. Figure 4 is the result of dynamic simulation after putting the optimal parameters into TRACEWIN.

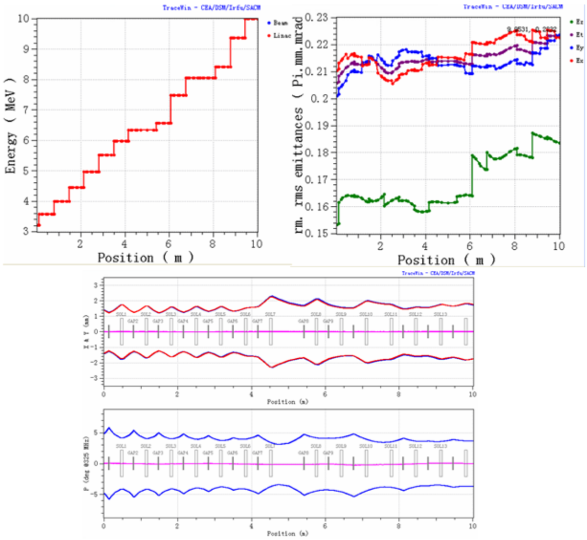

Figure 4: Result of TRACEWIN operating with the hardware optimal parameters.

CONCLUSION

Using FPGAs to complete the dynamics calculation is an absolutely new method in the accelerator physics. Above-mentioned method has its own advantages in speed and latter maintenance. The linear space charge and optimal algorithm have been applied in this method. This method will be tested on the 25MeV linac of C-ADS in the following work.

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